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TECHNICAL NOTE

AN OVERVIEW OF TROPICAL CIRCULATION

By Capt Frank [illegible]

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13. Abstract: This is a report on the tropical circulation and its role in supporting the larger general circulation system. The historical presentation of general circulation theory, the influence of tropical circulation on heat and momentum budgets, and localized circulation patterns are discussed. The subject of tropical cyclones has not been included in this report.

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Preface. This technical note is an overview of tropical circulations and their interaction with the general circulation. Keeping within the general scope of this subject this note <u>does not</u> discuss two major subjects associated with the tropics: energetics and tropical cyclones.

The driving force behind the global circulation is the differential heating between the tropics and the polar regions. Tropical circulations support the global general circulation by transporting excess energy out of the tropics to the mid-latitudes. On the global scale, tropical circulations are the stabilizing mechanisms which keep the earth-atmosphere heat budget in balance through continuous interaction with extra-tropical events. Locally, within the tropical latitudes, land-sea breeze circulations help moderate tropical climate.

The material presented in this technical note was developed from several authoritative sources which are cited in the bibliography at the end of the memo.

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CHAPTER 1

GENERAL CIRCULATION

1.1 **Background.** Modern climatology has undergone a great deal of change over the past 40 years. At one time, the primary work of climatologists was the classification of observed climate patterns. Koeppen and Thornwaite were two of the foremost experts in this field of descriptive climatology. Today, this descriptive climatology is more likely found in the geography rather than the meteorology department on most university campuses.

The advent of computer technology has transitioned traditional climatology into a dynamic science whose cornerstone is the climatological modeling of the earth-atmosphere system. General circulation theory is the basic element of climatological modeling, the accuracy of which is a function of how well atmospheric processes are understood and translated into computer algorithms.

1.2 **Climate Models.** Climate models have many applications. These include forecasting the effects of nuclear winter, depletion of atmospheric ozone, and measuring the "greenhouse effects" on the 21st century climate. In addition to these global applications, several specialized models help forecast climatic impacts on the local level. The effects of droughts, floods, and receding shorelines on the fragile local economies and social structures which dominate the tropics can have very significant, even life threatening, impacts on local communities.

These climate models are sets of computer algorithms representing the physics of the atmosphere. The "run" of the model is typically "initialized" using a set of mean atmospheric data. One iterative cycle is completed when the data are processed through the algorithms. The output from this cycle is a new set of data. This new data then becomes the new initial data for the next run as the process is repeated over and over again. Each iteration represents a step through time, 5 minutes or 5 days, depending on how the model is set up. This iterative process continues until a state of equilibrium, or stability in the data output, is reached which is considered the climatic state of the atmosphere. This "climatic" solution is a function of the accuracy of the original initializing data and the software's representation of the true atmospheric processes. One way to improve the accuracy of these models is to increase our knowledge of the general circulation.

1.3 **Energy Redistribution.** The general circulation is important because it is the earth's primary energy redistribution mechanism. The reason the global circulation exists is to break down the same energy discontinuities which create it. Once the circulation is established, it is constrained by other physical affects - momentum and rotation - which further sculpture its form.

1.4 **History**. General circulation theory is concerned with the large scale features of atmospheric motion which appear after some mean state of the atmosphere is reached. The theory dates back to Hadley (1735) and his simple description of the meridional circulation.

The famous astronomer, Halley (1686), was one of the earliest to describe the general circulation through detailed accounts of the trade winds. It is George Hadley who is credited for bringing circulation theories to the forefront of the scientific community and as such is regarded as the father of general circulation theory. In 1735 Hadley concurred with Halley that the distribution of solar heating would promote upward vertical motion in the lower latitudes and descending motions at the poles. Hadley's model of the circulation system was completed by equatorward flow in the low levels and poleward flow in the upper levels. Hadley explained the presence of the trades and westerlies based on the direct, thermally driven, meridional cells originating in the tropical belts of each hemisphere. Thermally driven means they are formed and maintained by local thermally (heat) related events, specifically large scale tropical convection.

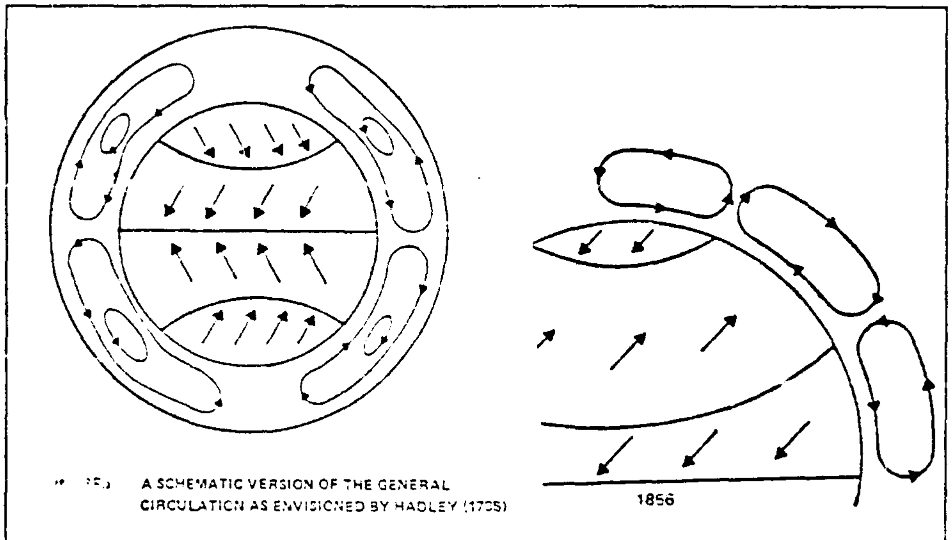

Figure 1a: Hadley's Model, 1735. 1b: Classical 3-Cell Model,1856.

In Hadley's model the circulation is symmetric about the equator. Remember, this model was developed from a very limited observational record set and accounted for the observed low level equatorward flow in the tropical belt. The earth's rotation would cause this flow to be deflected, and ultimately to form the easterly trades. Using the same reasoning, Hadley concluded the upper level poleward flow would be deflected to form the, as yet unobserved, upper tropospheric westerlies.

As observation techniques improved throughout the 19th century, this single cell model was modified. Contributions to circulation theory during this period were made by Dove (1837), Maury (1855), Ferrel (1856,1859), and Thompson (1857,1892). Ferrel is recognized as a major contributor to circulation theory. He made detailed studies of the N-S Coriolis deflections and was the first to introduce the complete equations of motion and define the thermal wind relationship. Ferrel agreed with Hadley that solar heating was the prime driver of the atmospheric circulations. His modifications of Hadley's theories led to his publishing a paper in a medical journal detailing the meridional, or classical, circulation model with its characteristic three cells. The middle cell is known as the "Ferrel cell" in recognition of his contributions.

Helmholtz (1888) offered a substantially new idea into circulation theory. He concluded that eddies, cyclones and anticyclones, were the principal agents in mixing the layers of the atmosphere with different momentum characteristics, thus preventing the development of stronger wind fields. Jeffreys (1926) was the first to note that meridional circulations alone were not strong enough to account for the required momentum flux to middle latitudes in order to balance frictional effects. He concluded eddies were necessary to compensate for the deficit in momentum transport.

This "new" concept that eddies were the primary support mechanism for the general circulation began to take hold. Transport theory moves away from thermally driven processes to eddies as the principal transport mechanism at work in the global system. Starr (1948) best summarized this new thinking through his observations that the global northward momentum transport requirement could be produced by troughs and ridges oriented NE-SW.

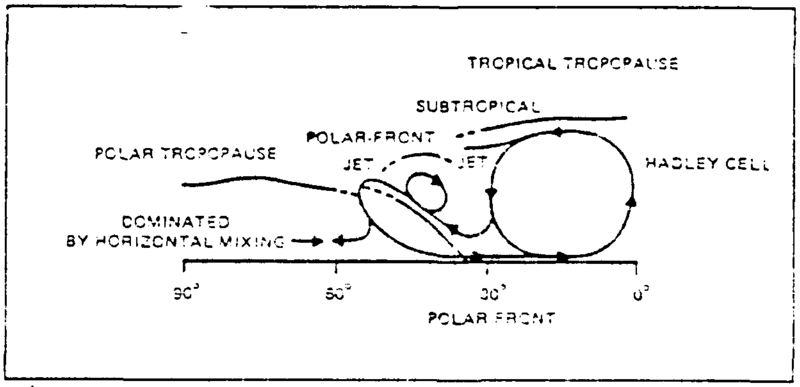

Figure 2. Palmen's model of the general circulation (1950).

In fact, both thermally driven and eddy transport processes support the general circulation. A Hadley-type circulation is observed in lower latitudes and is a major contributor to the meridional flux of momentum and heat. This is particularly true in the area of the Southeast Asia Monsoon where large scale convection supports a major portion of the Hadley circulation. At the same time, eddies also play a significant role in the transport process.

Another theory evolved in the late 1950's when Riehl and Malkus (1958) showed the Hadley and eddy transport processes alone could not transport enough mass to keep the global energy system in equilibrium. They proposed a "hot tower" theory which accounted for large volumes of mass being transported by the towering cumulus cells in the ITCZ. Suffice it to say, there are many large scale features in the atmosphere working to maintain the system in equilibrium. Each plays a significant role in defining the tropical and general circulations.

CHAPTER 2

AVERAGING TECHNIQUES

2.1 **Zonal Averaging.** Global scale circulations are often discussed in terms of time and space averages. Typically, circulations are presented as monthly, seasonal, or annual means which suppress synoptic events and allow investigators to see how the basic system is flowing. The smaller scale synoptic events, referred to as perturbations, are suppressed and the large scale features such as the Hadley cells and jet streams are seen clearly.

A brief illustration can help clarify this point using the notation followed by Lorenz (1967). A quantity X can be separated into components with reference to a time or space scale: a mean component and a perturbation (departure from the mean) component. As an example, you measure the wind at a station and find it is out of the northwest at 17 knots. Let us also assume that the average wind recorded on this day is out of the west at 11 knots. We could break the observed wind into its components: approximately an 11-knot westerly mean and a 13-knot southerly perturbation. This concept is expressed as:

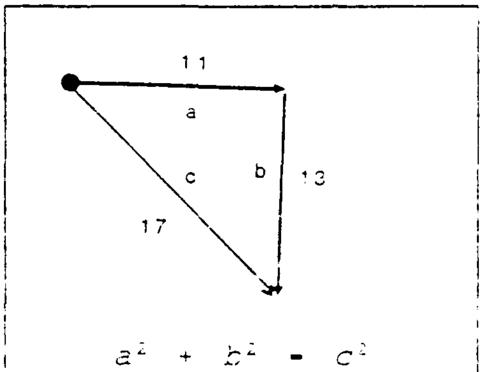

Figure 3. Wind Component Example.

$$X = \overline{X} + X' \tag{1}$$

Quantity	=	time avg mean	+	deviation from the mean

where the "bar" indicates an average and the " ' " indicates the residual left when the mean is subtracted from the quantity X.

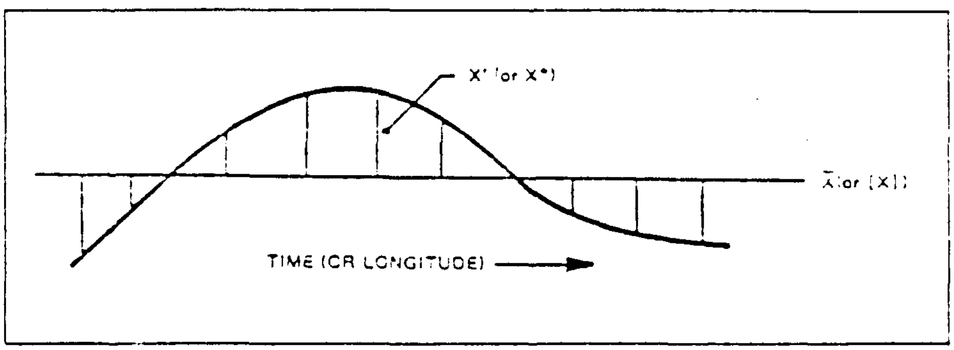

Figure 4. Perturbation schematic.

In addition to time averages, meridional (north-south) and zonal (east-west) averages can also be calculated.

The wind components can be broken into their meridional (v) and zonal (u) components. If you average the winds around the circumference of the earth at a given latitude you would end up with only a mean meridional (v) wind as the average u component sums to zero. This is the mean meridional component of the wind and is used to describe the large scale features of atmospheric circulations and their associated energy transports within the atmosphere.

2.2 **Eddies.** "Eddies" are another atmospheric constituent which arise in discussing the circulation. We have discussed how the circulation consists of a mean component and a perturbation element which is the departure from the mean. These perturbations are referred to as eddies. Transient eddies average out to zero when the average is taken with respect to time. This means the eddy may oscillate in time about the mean at any given data point, but its average is zero when viewed from a fixed point along L.

An example of a transient eddy is a middle latitude trough or ridge system which migrates from west to east. When viewed from a fixed point, there will be pressure oscillation about the mean flow when the trough passes and then when the ridge passes. The mean, over a long record period, of all of these perturbations will equate to zero. Standing eddies tend to persist in some geographical locations for an extended period of time. An example of a standing eddy would be the Bermuda High or Icelandic Low.

2.3 **Averaging Techniques.** In meteorology several different types of averaging techniques are used. Each additional computation in the averaging process smoothes the data and induces more error into the final solution. Even so, averaging techniques are very useful tools to bring out the major large scale circulation features and to isolate smaller scale terms embedded in the flow. Several examples of how averaging techniques have been used to highlight specific aspects of tropical circulation patterns are shown here.

2.3.1 **Seasonal Means.** Figure 5 represents the 200-mb velocity potential profile and irrotational velocity vectors as a three-month winter (Dec-Jan-Feb) mean covering the period from 1979 to 1986. Using a seasonal mean brings out the major features of the general flow which, for this property, indicates centers of divergence and convergence at 200 mb. The high located in the western Pacific is the central location for the major north-south (Hadley) and east-west overturning motions.

2.3.2 **Zonal Mean Meridional Component.** Using the same data, we also can construct the 200-mb zonal mean meridional velocity components shown in Figure 6. Averaging around a latitude circle and computing the monthly (time) average of the meridional components helps highlight and show the strength of the Hadley circulation. The positive (negative) values in this figure represent northerly (southerly) flow. The zero contour is the 200-mb divergence line which represents the ascending branch of the equatorial Hadley cell. This illustration shows how the Hadley cell shifts back and forth across the equator in tandem with the seasonal migration of the solar insolation maximum. This type of technique allows a detailed study of the intra-annual relationships of meteorological events.

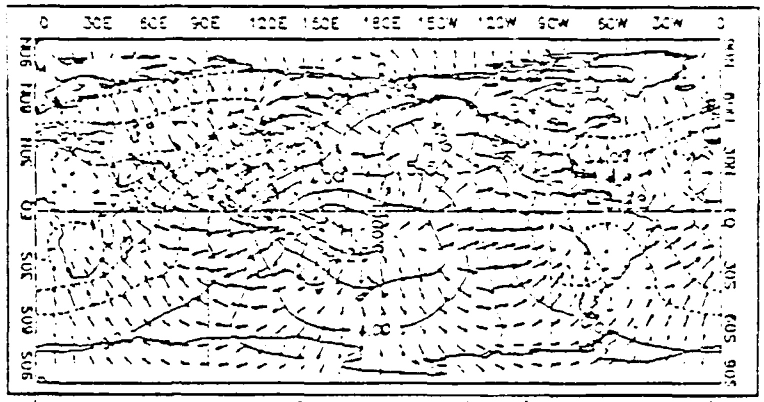

Figure 5. 200-mb Mean velocity potential and irrotational velocity vectors, Dec-Jan-Feb.

2.3.3 **Mean Zonal Component.** Figure 7 shows the mean zonal divergent wind for the two major convective latitude belts: Dec-Jan-Feb, 15°N to 15°S; and, Jun-Jul-Aug 0°N to 30°N. Positive (negative) values are eastward-(westward) directed 200-mb irrotational velocities computed as time and space averages. The magnitudes appear to be very even between the two seasons but there is a pronounced shift to the west of 60° between them. The easterlies are associated with a counterclockwise cell in the vertical plane with a rising branch over the monsoon region and a descending branch over Africa. These westerlies over the central Pacific are referred to as the Walker circulation, the dynamics of which are shown in Figure 7.

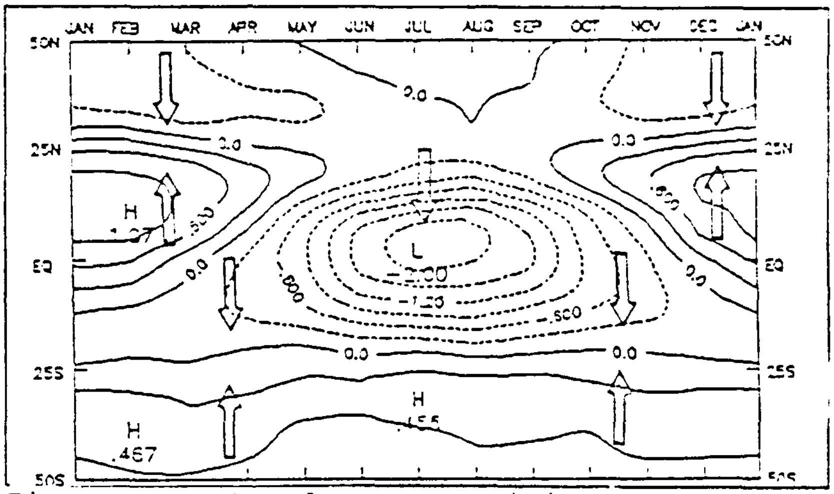

Figure 6. Zonal mean meridional velocity, 1979-1986.

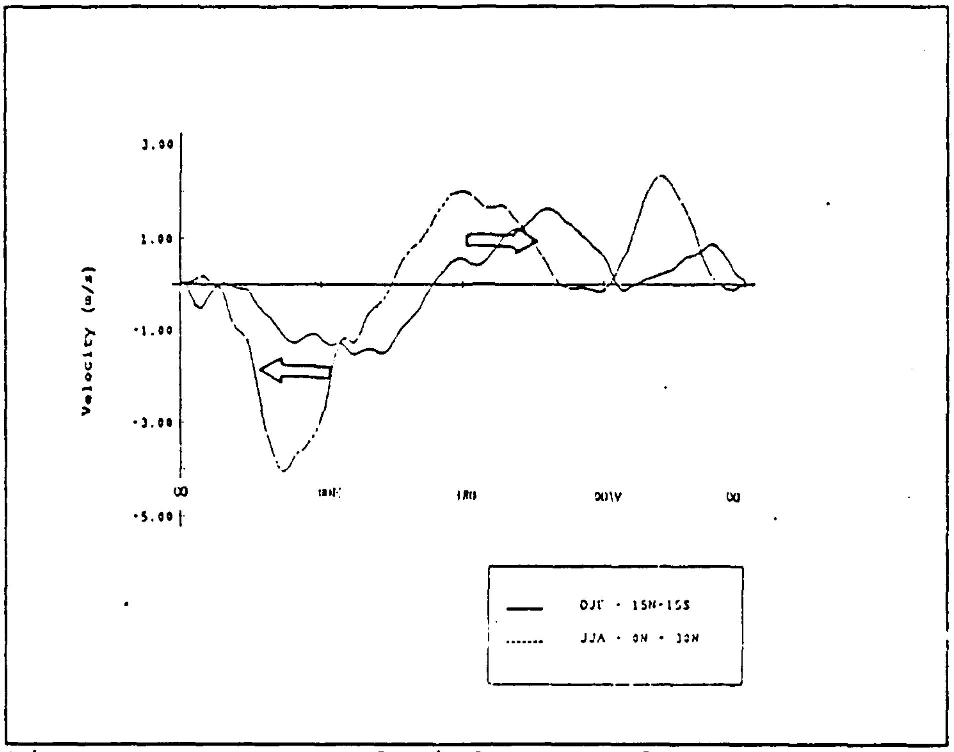

Figure 7. Mean zonal wind averaged from 15N to 15S latitude for Dec-Jan-Feb and 0N to 30N latitude for Jun-Jul-Aug. Data covers 1979-1986.

CHAPTER 3

ATMOSPHERIC FORCING

3.1 **Definitions.** Lorenz (1979) classified climate or weather variations into two types: forced and free. Climatic changes over extended periods are usually in response to some external condition referred to as forced motions. For example, Lorenz cites changes in either solar activity and the earth's orbit as the types of external conditions which would cause forced changes on the amount of solar insolation received at the surface. Other external influences include topography, which has a frictional effect, and Coriolis and centripetal forcing which are functions of the earth's rotation. These are also considered external forcings on the system.

3.2 **Cause-and-Effect.** Forced variations usually occur over large geographic areas. Global heating gradients responsible for the large-scale circulation are an example of the large-scale nature of these events. The variations in heating between low and high latitudes usually come to mind, but land-sea contrasts on the zonal plane are also included here.

3.2.1 **Thermal Capacity.** Topographic variations include those induced by differences in thermal capacities of surfaces. The thermal capacity of a substance is the ratio of the heat absorbed (or released) to the corresponding temperature rise (or fall). This is dramatized by the difference in thermal capacities of water and land. Water has a high thermal capacity which means it takes a lot of heat to change its temperature. This is important to us because it also means that water retains its heat for a long time. In contrast, soil has a low thermal capacity which accounts for its rapid diurnal temperature swings. Weather forecasting would be very simple if external forcings were eliminated because weather would remain fairly constant.

3.2.2 **Angular Momentum.** One of the major forced motions affecting the atmosphere is angular momentum. Byers (1959) described the conservation of angular momentum this way:

> "as the distance from the center of rotation to a particle becomes smaller, the particle must increase its linear and angular velocity".

This principle is demonstrated in the actions of a figure skater on ice. As the skater starts a spin with arms extended the rotational speed is relatively slow. By bringing the arms into the chest the skater becomes a blur because the rotational speed has increased dramatically. The movement of air parcels poleward brings them nearer to the earth's axis of rotation. The momentum equation requires this action to be accompanied by an increase in angular velocity and an acceleration to the east.

If all surface winds were blowing in a constant direction, say to the west, while the earth rotates toward the east, there would be a decrease in the earth's rotation rate. To maintain the earth's equilibrium, momentum is constantly being removed from the atmosphere in the tropical easterlies and transferred to the surface in the mid-latitude westerlies. Similarly, angular momentum is being extracted from the earth by the atmosphere in regions of easterly surface winds which are in opposition to the direction of the earth's rotation.

Easterly winds are observed at the surface in the tropics and westerly winds are observed in the middle latitudes. To support

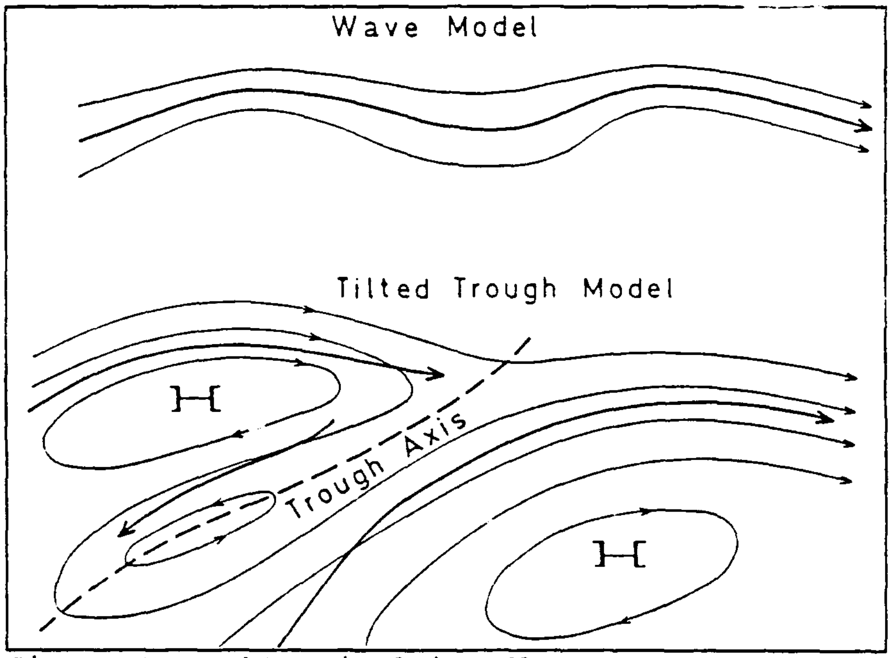

Figure 8. Subtropical jet flow patterns (200-mb level).

these observed wind patterns there must be a flux (flow) of angular momentum from the equator toward the poles to supply the momentum lost there. One method of transporting momentum is by eddy fluxes. Wave troughs are the mechanism in the circulation which helps carry properties like momentum away from or towards the tropics. The separation of the subtropics by high pressure cells facilitates this type of transport process as illustrated in the streamline patterns in Figure 8.

In the tropics, the southwesterly flow in this tilted short wave trough is "warm" and the northerly flow is "cold" air. This alignment supports both heat and momentum transfer processes.

3.3 **Coriolis Force.** A second forcing motion is the <u>Coriolis force</u>.

The Coriolis force is an apparent force which exists because our frame of reference is a rotating system. The Coriolis parameter is a function of the earth's angular velocity ( ) and latitude ( ) and is defined as:

$$f = 2\,\Omega\,\sin\phi \qquad (2)$$

The direction of the Coriolis force is always to the right of motion in the Northern Hemisphere. Because the Coriolis force is always "perpendicular" to the direction of motion, it never affects parcel velocity; however, it does affect parcel trajectory.

3.4 **Free and Forced Variations.** Lorenz defines free variations as those which do not depend on external conditions but usually develop on their own. These conditions account for most of the daily weather changes on the synoptic scale. A change in the local weather induced by a frontal passage is an example of a free variation. Frontal systems occur because of zonal instabilities within the circulation and not because of external variations.

An example of a free variation is baroclinic instability. This type of instability is very prevalent in the mid-latitudes and is responsible for the growth of small amplitude disturbances into large-scale traveling waves. These waves have a very strong impact on local weather conditions. Their effects are usually felt over several days which is the average time it takes for the waves to travel one full wavelength.

Forced motions affect the lasting quality of features in atmospheric patterns. Those caused by topography, such as a continent, will not vary much over time because the topographic feature remains constant. Conversely, thermal forcing associated with sea surfaces will reflect the transient nature of the water body which is causing the forcing motion. As large bodies of water warm or cool, or undergo similar temperature swings because of changes in the currents running through them, the forcing exerted by the body of water will also change.

CHAPTER 4

TROPICAL CIRCULATION - OVERVIEW

4.1 **Background.** The accuracy of general circulation theories is limited by our understanding of the physics which govern the atmosphere. The term "physics" can mean several things but we use it to refer to the physical processes which control the atmosphere and force it to behave the way it does. Once we have articulated these physical processes into a mathematical form, the next step is to translate them into a computer model. To do this we must be able to translate the "physics", those physical constraints as we know and understand them, into computer algorithms and processes.

As an example of a physical constraint, consider that the earth-atmosphere system maintains itself in thermal equilibrium. We know this is true because we can measure insolation and make observations of the temperatures around the globe. If there was not some underlying process at work, we know that the tropics would be continually heating up and the poles would keep getting colder. Observations prove that except for annual, seasonal, or diurnal changes the earth's temperature remains fairly constant. This underlying process is an example of a "physical" constraint on the system which forces heat out of the tropics towards the poles.

4.1.1 **Hadley.** As we have stated, Hadley was the first to publish a descriptive climatological model of the general circulation using limited observations of the circulations at the surface. His simple model neglected any zonal (east-west) discontinuities around a latitude which means he ignored east-west forcings either due to pressure gradients or topography.

This assumption eliminated any aberrations which would distort the flow patterns on the zonal (east-west) plane. The result is a very simplified representation of the circulation as large rings of air which are symmetric about the equator like giant donuts.

4.1.2 **Energetics.** Excess heating in the tropics provides the energy to start these rings rising. Likewise, heat deficits at the poles cause comparable sinking motions. The result of this rising and sinking at opposite ends of the hemispheric plane is the formation of an upper-tropospheric circulation directed from the equator to the poles. This is in compliance with the physical constraint of "mass continuity" which is the tendency for mass to seek an equilibrium and not pile up in one area while a deficit exists somewhere else in the system.

4.1.3 **Ageostrophic Flow.** This type of circulation is known as "ageostrophic" motion because it is driven by divergent and convergent processes. Once established, the poleward flow acquires a westerly component because of the influence of momentum and Coriolis forcing in the Northern Hemisphere. Similarly, the return flow in the lower troposphere acquires an easterly component from the same forcing mechanisms. These forcings provide the "geostrophic", or turning component, of the circulation which is predominant in mid-latitudes. This single cell model is the basis of the original Hadley model of 1735.

4.2 **Three-cell Model.** The flaws in this model became apparent when observational data became available. Persistent surface winds towards the west, in opposition to the earth's eastward rotation, would continually extract momentum through frictional contact and decrease the rotation rate. In addition, the model does not adequately account for the continuous loss of heat by the system through thermal radiation to space. Resolution of these problems led to the classical three-cell model.

In this model air rises near the equator, moves poleward under the constraints of angular momentum and Coriolis forcing which give it an eastward component. This forcing is increased as the air moves further northward because both of these forcing elements are functions of latitude. As latitude increases, so does the magnitude of the force. The result is the flow takes more of an easterly turn as it moves northward.

During this process, the air continues to radiate energy to space as it moves poleward. This air eventually cools through radiative losses and begins a gradual descent. Observations confirm this descent occurs in the vicinity of 30° latitude. The descent brings the westerly momentum of the upper tropospheric flow down to the surface. Friction between the eastward rotating surface of the earth and the westward moving winds decreases the wind speed as momentum is transferred from the atmosphere to the earth.

As air sinks it converges mass (air particles) at the surface. This convergence, when met by the immovable surface, causes the mass to spread out with some of the flow turned back towards the equator. Coriolis and momentum forcings combine to turn the zonal components of this return flow from westerlies, to neutral, and finally to easterlies. This total cellular pattern is known as direct thermal circulation from the tropics to the mid-latitudes and was named the Hadley cell in honor of the pioneering work of George Hadley. This cell is one of the primary support mechanisms of the global circulation.

4.2.1 **Model Discrepancies.** Several discrepancies related to this classical theory are discussed by Hess (1959). Among them, modern meteorologists consider latent heating, not direct radiative processes, as the major energy source heating the atmosphere and thereby driving the general circulation. Remote sensing techniques of the last 30 years have confirmed that the tropical atmosphere, left to its own radiation processes, is actually a radiative sink. The primary influence of solar insolation at the surface is exerted through the large scale evaporation occurring in the tropics.

Hess also addresses the model's failure to account for the momentum transfers necessary to support the observed circulations. In the mid-latitudes, where upper-tropospheric flow is towards the equator, the wind should be acquiring an easterly component because of the Coriolis force acting on the flow. To support these observed westerlies there must be some additional momentum transfer process at work.

Rossby (1941) suggested large-scale eddies, waves in the horizontal zonal flow patterns, act as conduits for momentum transfer to the mid-latitudes. These wave patterns, caused by disturbances in the east-west plane, invalidate the assumption of continuous zonal rings we made earlier.

CHAPTER 5

TROPICAL CIRCULATIONS - OBSERVATIONS

5.1 **General.** The subtropical belts of high pressure are easily identifiable as Highs on surface pressure charts and anticyclones on streamline charts. The most persistent cells are the: North Atlantic, North Pacific, South Atlantic, South Pacific, and South Indian Ocean Highs. These high pressure cells are very important because they help define the tropical trade wind circulation.

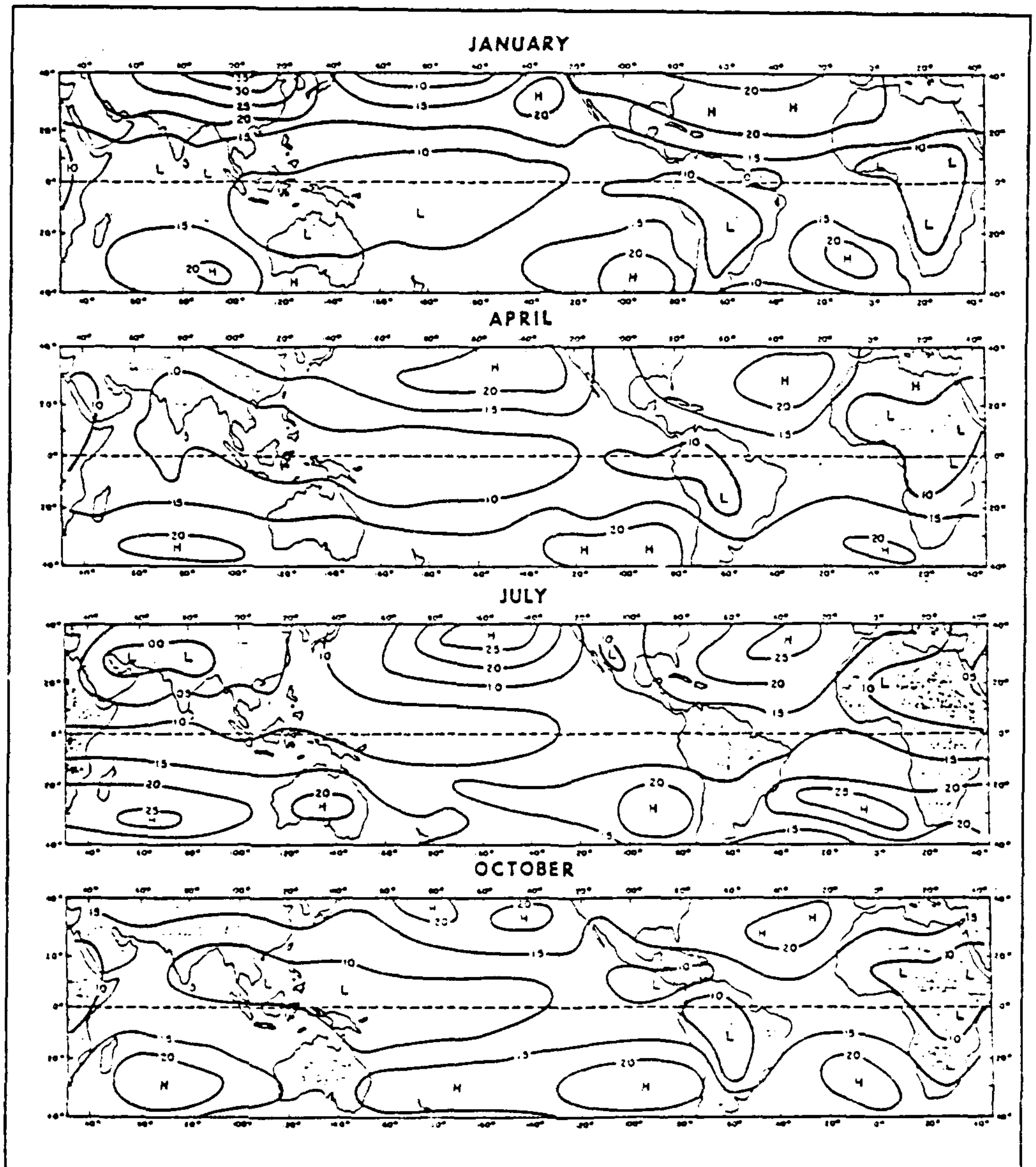

Figure 9. Mean sea-level pressure in millibars (Crutcher and Davis).

The subtropical highs are close to the equator during the winter and move poleward in summer. The North Pacific, North and South Atlantic, and Indian Ocean Highs are also displaced to the East in winter and to the West in summer. The latitudinal displacements follow the sun's annual transition between hemispheres. Topographical forcing, specifically the influences of land and sea contrasts, contribute to zonal movements.

The equatorial trough of low pressure and the subtropical high pressure belt move toward the equator during the Northern Hemisphere winter (Dec - Feb). At the same time, the subtropical high pressure belt of the Southern Hemisphere is also displaced to the south.

The upper tropospheric circulation over the Northern Hemisphere during winter is dominated by the Subtropical Westerly Jet which can extend into the tropics. During this period, Northern Hemisphere upper-tropospheric easterlies flow from 0-10° S and extend from the Central Pacific across the Indian Ocean into the Africa.

During Northern Hemisphere summer (Jun-Aug), the upper-tropospheric circulation over the Northern Hemisphere is very different. Over the tropical Northern Hemisphere, the Subtropical Westerly Jet is no longer present. Anticyclonic cells are found over North America and throughout the subtropical Asian-African belt. The Tropical Easterly Jet extends from Southeast Asia across the Indian Ocean to Africa on the equator side of the high pressure belt.

There are "tilted troughs" oriented from Southwest to Northeast" located over the middle of the Pacific and Atlantic. A strong westerly jet can be found in the Southern Hemisphere poleward of the High pressure belt. This jet extends around the globe with the jet maximum over Australia-New Zealand.

5.2 **Subtropical Westerly Jet.** One of the most prominent features associated with the circulation in the Northern Hemisphere is the Subtropical Westerly Jet. It is found above the descending portion

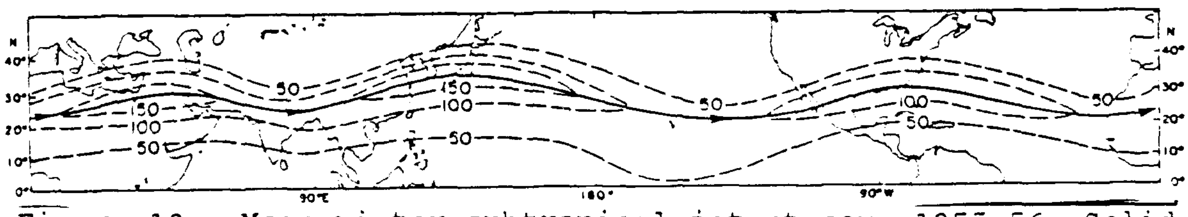

Figure 10. Mean winter subtropical jet stream, 1955-56. Solid line is mean jet core and dashed lines are isotachs in knots. (after Krishnamurti).

of the Hadley cell where there is a convergence of westerly absolute angular momentum. The jet maximum is correlated to the strength of the Hadley circulation which is at maximum strength during the Northern Hemisphere winter. In addition, the confluence of the upper-tropospheric branches of the Ferrel and Hadley cells help define the "Subtropical Front".

This "frontal zone" is very supportive of the jet. However, as it overlies prevailing subsidence in the lower troposphere, the Subtropical Front does not support similar weather characteristics as the Polar Front. The Subtropical Westerly Jet is important because it affects large-scale convection in the lower troposphere and supports many of the mid-latitude synoptic events.

5.3 **Monsoon Circulation.** The monsoon circulation is an intense localized circulation system. To be classified as a monsoon type climate, the winds must reverse in direction between the summer and winter. This reversal characterizes monsoonal flow inland from colder oceans toward warmer continents during summer and from cold continents toward warmer water bodies during winter. The general circulation system which characterizes this event is illustrated in Figure 11.

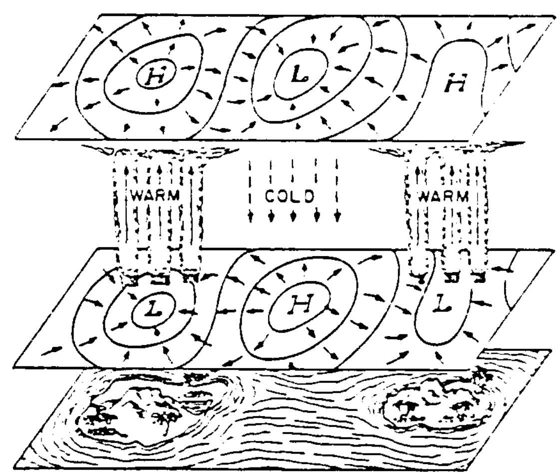

Figure 11. Monsoon circulation schematic.

The principle driving mechanism for the monsoon circulation is differential heating between land and sea surfaces. This differential creates a pressure gradient which drives the winds from high to low pressure with rotation induced by the Coriolis forcing.

The primary large-scale monsoon regions are shown in Figures 12a and 12b for the Northern Hemisphere summer and winter, respectively. Included are the East Asia Monsoon (EAM), the Indian Southwest Monsoons (ISWM), the West African Monsoon (WAM), and the North American Summer Monsoon (NASM). Other monsoons are: the Northeast Winter Monsoon (NEWM), the Australian Northwest Monsoon (ANWM), the North American Winter Monsoon (NAWM), and the African Winter Monsoon (AWM).

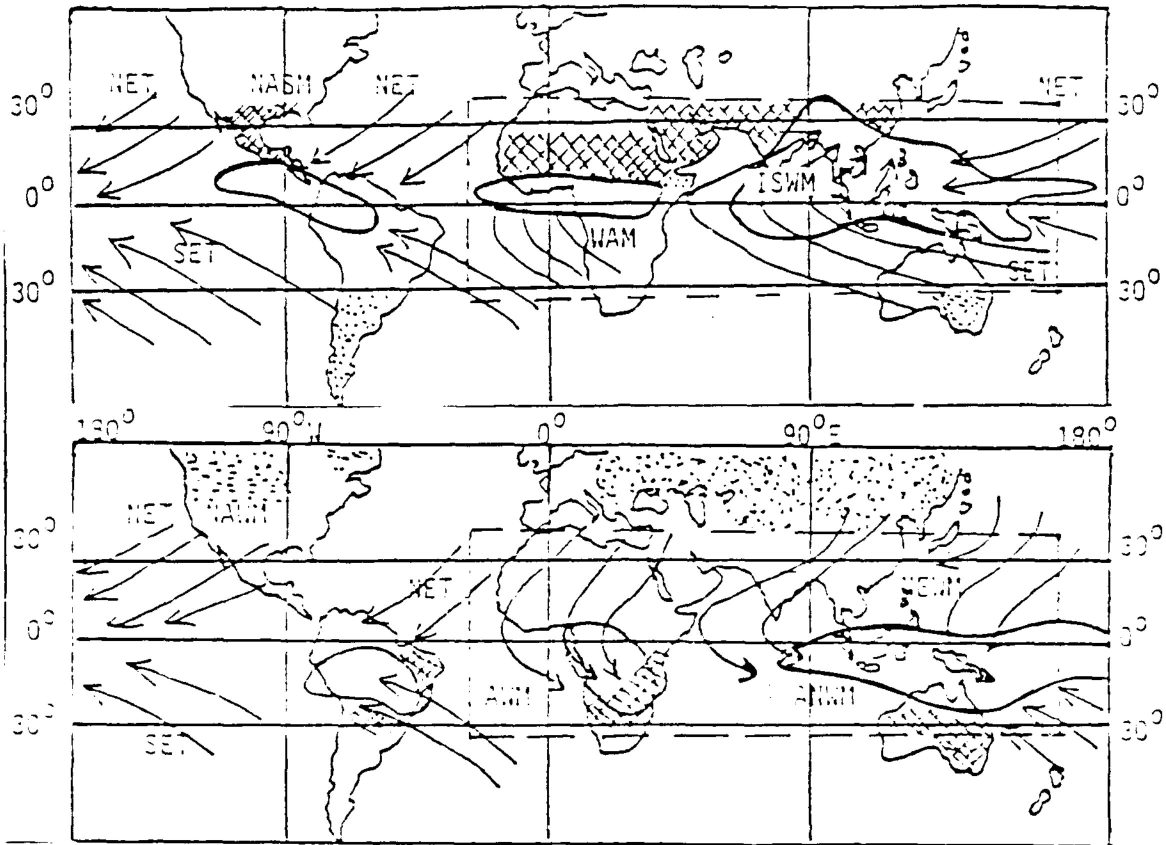

Figure 12. Monsoon Climatology.

5.3.1 **The Summer Monsoon Over Southeast Asia (SEA).** We use the SEA summertime monsoon as described by Ramage, Brody, Adler, and Brand in their <u>Diagnosis of the Summer Monsoon of Southeast Asia</u> (1969) to highlight characteristic monsoon patterns.

The schematic in Figure 13 represents the low-level features of the summertime monsoon over this region. Part A depicts the trade wind regime between the subtropical ridges (dashed lines) of the Northern and Southern Hemispheres. Part B shows an east-west pressure trough (dotted line) in the Northern Hemisphere whose intensity is sufficient to produce a westerly current on the equatorward side. The dash-dot line represents the resultant clockwise rotation required to couple the westerlies and easterly trade winds which establishes the indicated ridge line. In C the system expands to the south pushing the ridge line over the equator. Part D is the representation of the low-level flow during the height of the summer monsoon from India to the Philippines with 100°E longitude near the center of the diagram. The clockwise rotating wind is south of the equator near India and north of the Equator near the Phillipines.

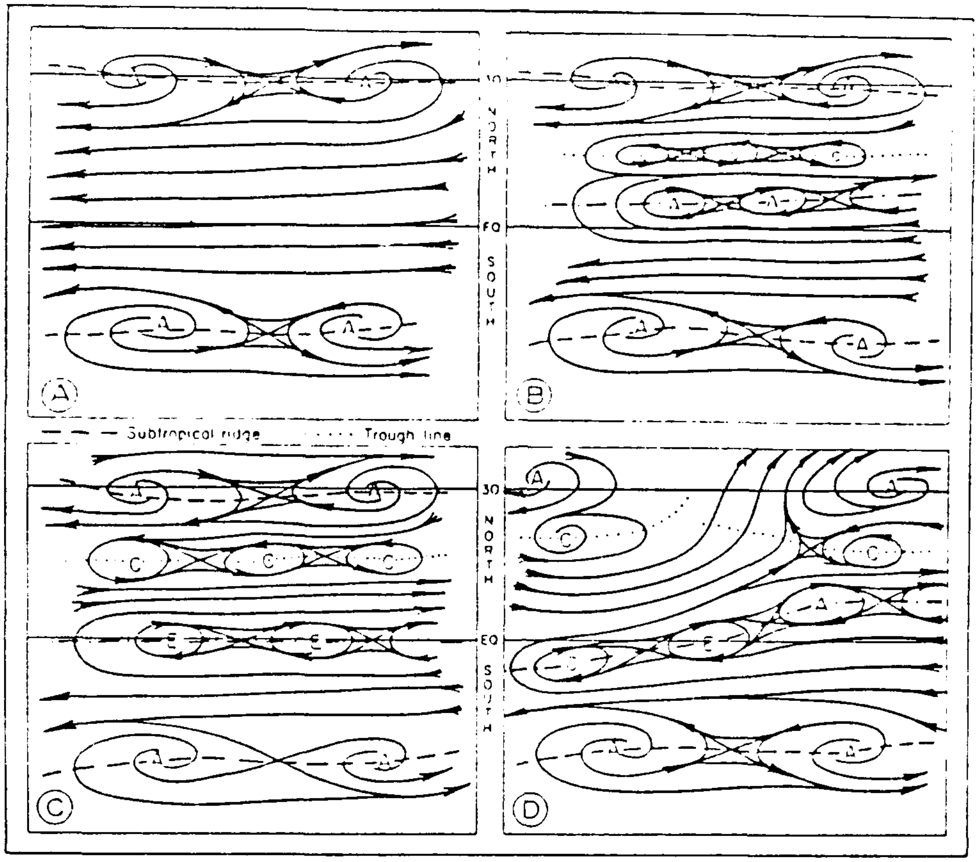

Figure 13. Schematic of mean low-level features of SEA summer monsoon. (after Sadler, 1969)

Figures 14 and 15 show the mean flow patterns for May at 2000 ft and 200 mb (after Sadler, 1969). At 2000 ft westerlies extend from India through the majority of the Indochina Peninsula. In the months preceding May, the subtropical ridge extended across Indochina and the Bay of Bengal into central India. The increased heating of the Asian land mass and the associated decrease of pressure causes the subtropical ridge to retreat eastward to its present location. The trough line which extends from eastern India into Burma is the beginning of the monsoon trough. The trough from Borneo through the Malay Peninsula is an equatorial trough which is a feature of pre-monsoon conditions.

The mean flow for July at 850 mb and 200 mb is shown in Figures 16 and 17 after Sadler, 1969. The monsoon circulation has intensified as indicated by the intensified low-level westerlies which now project further to the east into the South China Sea.. The monsoon trough is oriented NW-SE across the South China Sea into the western North Pacific. At 200 mb the subtropical ridge has also moved north with easterlies extending northward to 30°N.

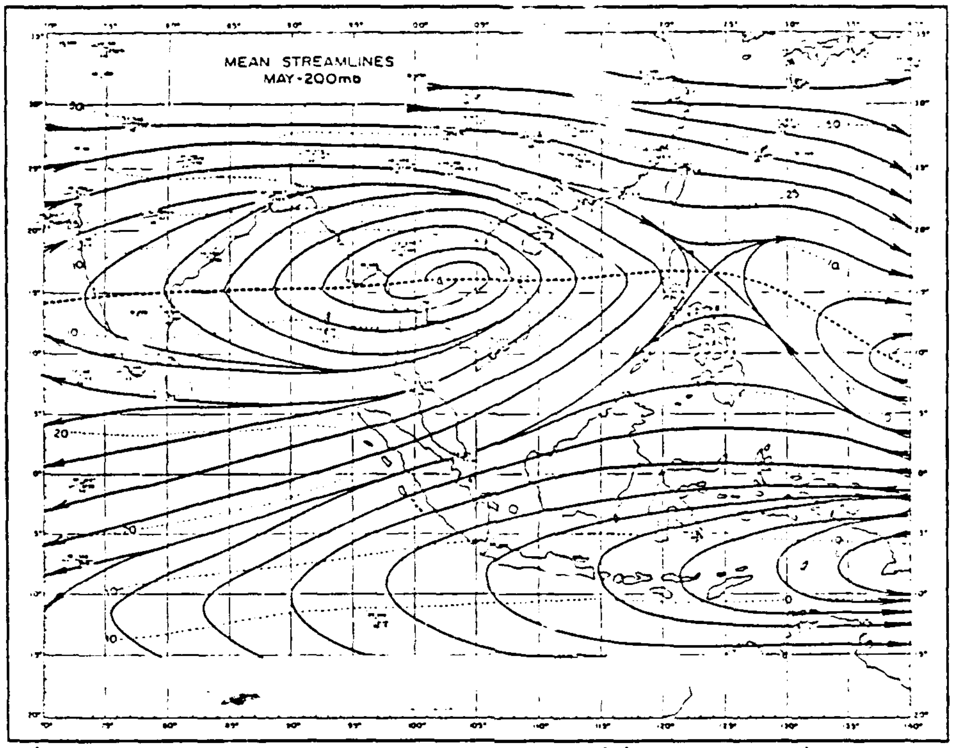

Figure 14. Mean 200-mb streamlines and isotachs (knots), May. (Sadler, 1969)

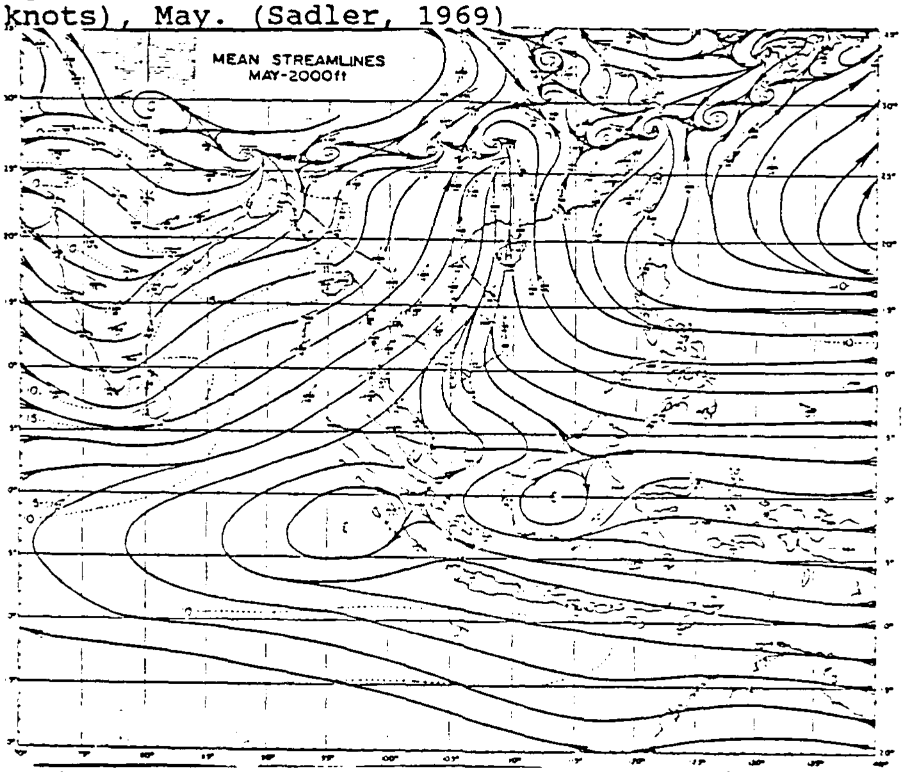

Figure 15. Mean 2000-foot streamlines and isotachs (knots), May. (after Sadler, 1969)

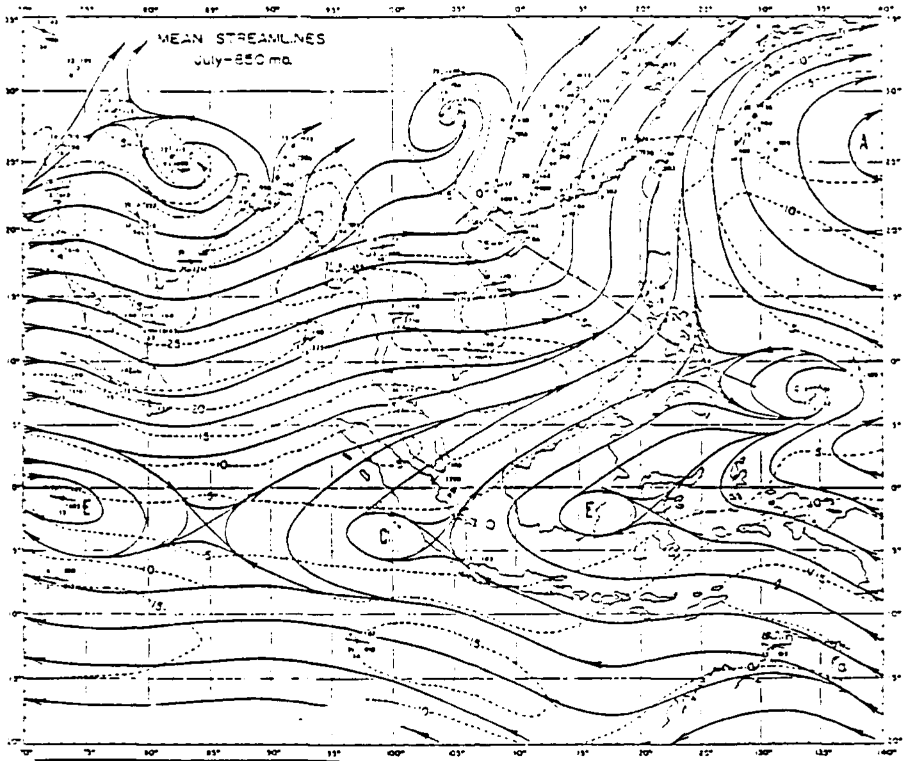

Figure 16. Mean 850-mb streamlines and isotachs (knots), July. (after Sadler, 1969)

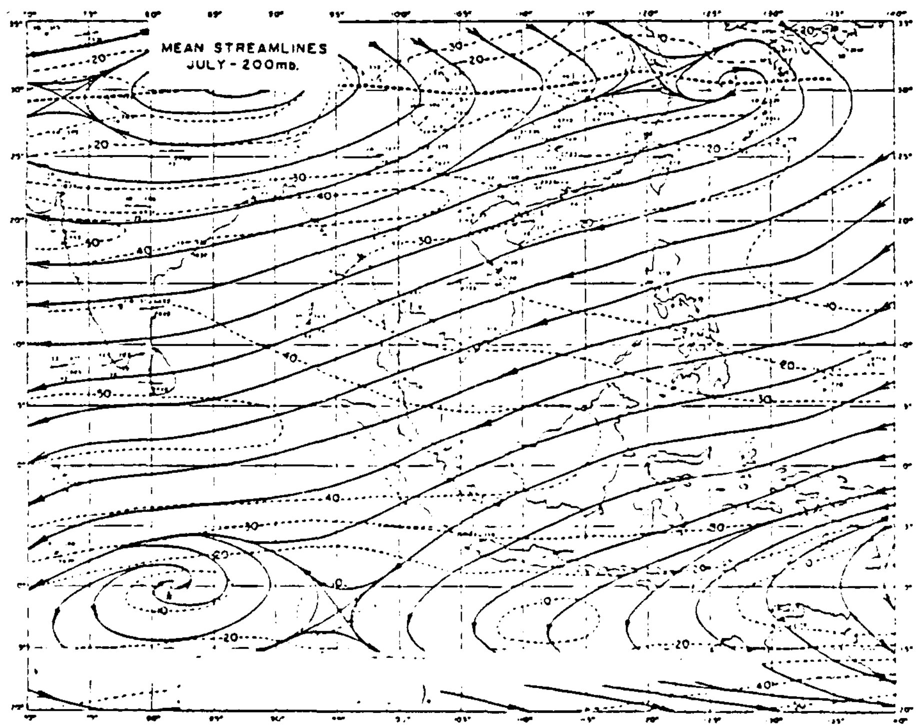

Figure 17. Mean 200-mb streamlines and isotachs (knots), July. (after Sadler, 1969)

5.3.2 **The Himalayas.** The Himalayas support the presence of the summertime monsoon over southern Asia. During the winter season, the upper tropospheric winds (200 mb) are generally westerly in relationship to the north-south temperature gradient which exists across this region. During the spring the insolation on the Tibetan Plateau increases as a result of the northward migration of the sun. This increased heating, together with a large release of latent heat from rainshower activity along the southern slopes of the Himalayas in Northeast India, causes substantial warming of the middle and upper troposphere over the Himalayas.

This heating weakens the normal north-south (warm to the south) temperature gradient over southern Asia south of 35°N latitude. By early summer there is a reversed temperature gradient (warm over the plateau and cooler to the south) which is strongest south of Tibet. The resulting flow pattern seen in the 200 mb chart is divergent over SEA which supports upward vertical motion characteristic of the monsoon.

5.3.3 **Synoptic Characteristics.** The monsoon is the result of a reversal on the normal N-S temperature gradient. The monsoon circulation typically begins forming in March with a completed monsoon circulation cell in place by late June. The circulation lasts until September which corresponds to the end of the summer season in this region. By mid-October the reversal back to normal is seen throughout the troposphere.

The monsoon trough which was referenced above is not a persistent feature. In contrast, it tends to form, disappear for weeks at a time and reappear at a new location. It stays close to areas of maximum air temperature and surface heating. Its close association with surface heating likely accounts for its preference to form to the north in the spring as the sun moves north, and then to the south in the fall as the sun moves in that direction.

CHAPTER 6

TROPICAL WAVE DEVELOPMENT

6.1 **Equatorial Waves.** Easterly waves are low-level synoptic type disturbances found in the tropics. Palmer was the first to call them "equatorial waves". A second type of disturbance is found in cold core vortices associated with the tropical upper-tropospheric 200-mb troughs of the North Pacific and Atlantic. The largest temperature anomalies (differentials) associated with these cold vortices is near 300 mb. They can move in either direction but primarily propagate westward at 5-6° longitude per day.

6.2 **Trade Winds and Shear Lines.** In the western tropical oceans, along the western borders of oceanic anticyclones, the trades have their maximum strength because of the incursion of mid-latitude depressions. This causes a steeper pressure gradient to form away from the centers of the subtropical highs. Accompanying these wind surges are discontinuities, or shear lines. These shear lines exist between the strong winds of the surge and the weaker winds of the trades nearer the equator. Convergence along the shear line is clearly visible in satellite imagery as "rope clouds" formed by the cumulus development. Shower activity in these zones is extensive.

Shear lines generate barotropic instability and disturbances develop and migrate westward in response to it. Given the lateral shear characteristic of these regions in summer, the growth rate of the disturbances is a few days and the dominant wavelength is approximately 3000 km. Since these disturbances remove energy from the mean flow, the flow can only remain steady if its energy is constantly replenished. The monsoon circulation provides this replenishment.

6.3 **Cyclonic Development.** Cold cyclonic centers imbedded in the flow cause maximum cyclonic vorticity advection ahead of them in the upper levels with maximum upward motion around the 300-mb level. Other factors enhance the convection supported by this vertical motion which in turn further supports the disturbances' overall structure. Eventually, the convection, which releases latent heat into the atmosphere, modifies the vertical structure from "cold core" to "warm core" at 300 mb.

CHAPTER 7

LOCALIZED TROPICAL CIRCULATIONS

7.1 **Walker Circulation.** The Walker circulation is an example of a persistent circulation localized within the tropics. This circulation is driven by an oscillating pressure center across the Pacific ocean. These oscillations were studied in detail by Sir Gilbert Walker (1928,1932) who referred to them as the Southern Oscillation (SO), a name which has taken hold in meteorological literature. Walker and Bliss (1932) observed that when sea-level pressure was high over the central and eastern Pacific, it was usually low over the Indian Ocean and Indonesia, and vice versa. Walker further observed that when there was lower pressure over the Indian Ocean and Indonesia, precipitation in that area tended to be above normal. These large-scale pressure oscillations have a great impact on the circulation within the equatorial tropics which define tropical and global weather patterns. Changes in mean wind, temperature, and rainfall observations in the Indian Ocean and Indonesian monsoon regions as well as the central and western equatorial Pacific are byproducts of these pressure fluctuations. Since Walker and Bliss first detailed the structure of this oscillation, observations confirm that the event occurs with a degree of regularity every two to seven years. To acknowledge his pioneering work in this area, the circulation pattern which is supported by this Pacific pressure regime is named the "Walker circulation".

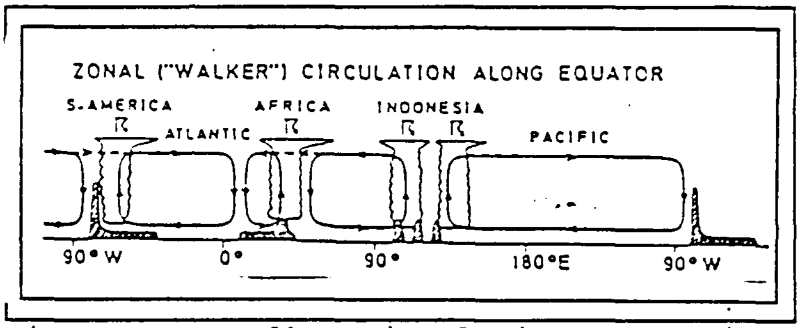

Figure 18. Walker circulation schematic.

7.2 **Diurnal Circulation Patterns.** Temperature patterns within the tropics are very persistent, especially compared to the large annual swings found in the extra tropics. The largest temperature variations are those associated with diurnal fluctuations which support local circulations. These fluctuations can exceed 10° C over land while sea surface temperatures remain fairly constant owing to the larger heat capacity of water.

The time scale of diurnally forced circulations is less than one day but they still can lead to strong topographic and mesoscale circulations. The strength of these circulations can strongly influence the spatial (area) pattern and diurnal cycle of cloudiness and rainfall. One classical example of this influence is the sea breeze effect found in island chains and coastal topography.

7.3 **Observations.** Figure 19 illustrates several flow configurations. Islands less than 100 km wide whose topography is less than 1000 m have a special effect. The northeast trades meet daytime sea breezes on the leeward side of the island where convergence and cloudiness develop. At night the trades oppose the land breeze on the windward side and combine with it on the leeward side.

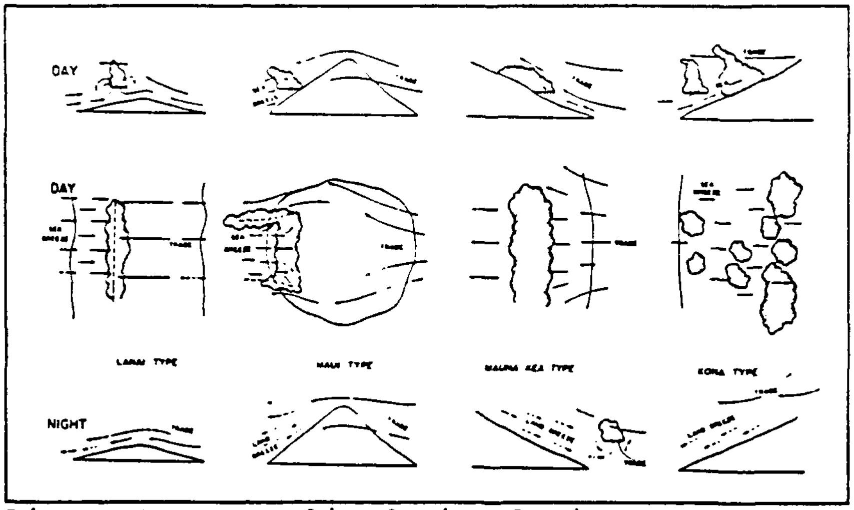

Figure 19. Localized circulation patterns.

On larger islands, with a significant topographic feature such as a volcano, the trade winds flow around the topographic obstacle causing heavy rainfall on the windward side. Daytime convection on the leeward side develops cloud streaks along the zone between sea breeze and trade wind systems.

On large mountainous islands, such as Hawaii, the winds cannot completely circumnavigate the mountainous terrain. The wind patterns developed on these types of islands usually support cloudiness and rain on their windward side. Strong trade winds through mountain passes can create hazardous conditions for low flying aircraft. At night the land breeze on the windward side flows counter to trades resulting in convergence and convection. During daytime, a convergence between the sea breeze and trade winds occurs on the leeward side (Kona type).

These effects are not limited to islands. Figure 21 illustrates the development of daytime cloudiness patterns around large islands with mountainous centers. Strong daytime convection develops over the mountains of the interior which is an elevated heat source. A lateral inflow of air is started and compensated for by subsidence around the island. This pattern is indicated by the clear ring in the figure. Trade cumuli are confined by this circulation pattern to larger distances around the island. The clear ring increases in width until the middle of the afternoon but contracts towards evening with the decay of convection over the central mountains.

Similar vertical motions, with more irregular shape than shown here, are commonly found in many tropical mountain regions. At night, surface winds are directed down slopes and valleys and the mountain peak clears. Concurrently, airstreams converge over basins where cloudiness develops. In the morning, the circulation induced by the topography reverses. Surface winds are directed up the slopes and valleys. Clouds form over the mountains in the midafternoon while the basins clear out. In late afternoon the downslope winds return.

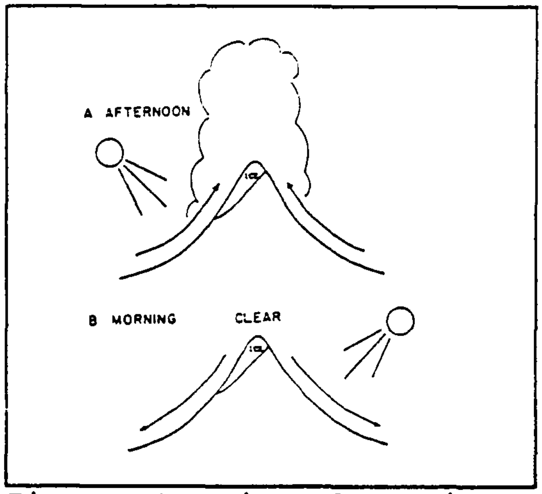

Figure 20. Diurnal forcings.

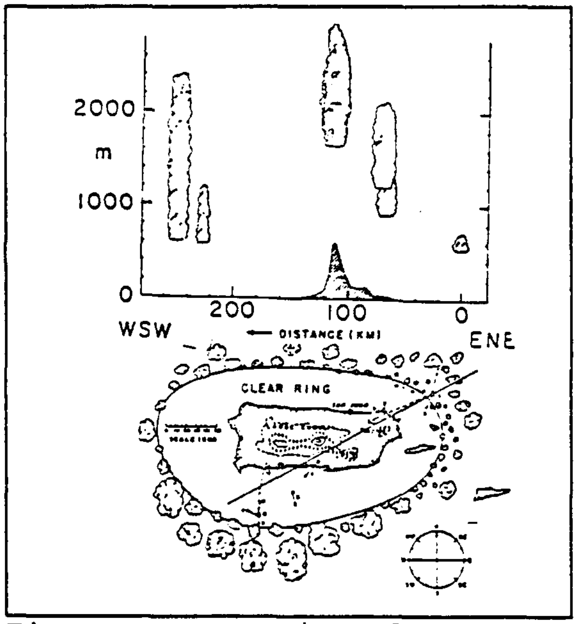

Figure 21. Diurnal thermal forcing on cloud development.

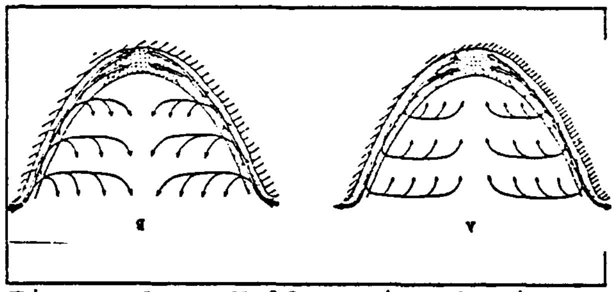

Figure 22. Valley circulations: (a) daytime, (b) nighttime.

SUMMARY

The general circulation of the atmosphere is a global event which is initiated and is maintained by the differential solar heating of the earth-atmosphere system. The tropical latitudes play a significant role in this global pattern because the excess heating found in the tropics is the fuel which drives the global circulation system. The tropical circulations are the mechanisms which deliver this fuel and thereby support mid-latitude synoptic scale events.

Circulations are the result of a physical system trying to keep itself in equilibrium. Locally within the tropics, several persistent circulation patterns are observed which develop in response to both large-scale and local forcing mechanisms. These local circulations help define the tropical environment and establish those characteristics which we refer to as tropical climatic conditions.

One of the major topics relating to the tropics which we did not discuss in this overview was energetics. Although we continually refer to the fact that the tropics as the energy source fueling the general circulation engine, we could not discuss the details of energy exchange and how energetics support the general circulation because it is beyond the scope of this circulation overview. Suffice it to say that excess heating in the tropical belt is translated into energy, primarily in the form of latent heat, which is then transported to extra-tropical latitudes to feed the instabilities that develop into mid-latitude weather patterns. This transfer is supported by such basic mechanisms as a north-south temperature gradient which supports meridional transfer. At the same time, the radiative losses in the atmosphere require a compensating upward transfer of heat from the earth's surface where there is a radiative surplus. The net result, in general, is a poleward and upward energy transfer.

The vertical transfer is supported by a wide range of vertical circulations. Simple cumulus development, towering cumulus development, tropical storms, and monsoons, all contribute to this vertical transfer process. These processes are important because they transfer sensible heat from the surface while carrying larger quantities of latent heat which is released in their ascending branches. This release represents a net heat gain by the atmosphere which corresponds to the heat loss at the surface due to evaporation over the large tropical water surfaces.

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